

# Electroweak Gauge Theories and Alternative Theories at a Future Linear $e^+e^-$ Collider

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## Abstract

The measurement of Standard Model processes tests the validity of the model at a given scale and is simultaneously sensitive to new physics through loop effects or interference with the Standard Model amplitudes. A variety of studies has been done to see what a linear collider in the energy range  $m_Z < \sqrt{s} < 1$  TeV can offer. The work that has been done within the ECFA/DESY workshop on linear colliders is reviewed, especially what was not included in the TESLA TDR.

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## Abstract

The measurement of Standard Model processes tests the validity of the model at a given scale and is simultaneously sensitive to new physics through loop effects or interference with the Standard Model amplitudes. A variety of studies has been done to see what a linear collider in the energy range  $m_Z < \sqrt{s} < 1$  TeV can offer. The work that has been done within the ECFA/DESY workshop on linear colliders is reviewed, especially what was not included in the TESLA TDR.

## INTRODUCTION

It is a common belief that the Standard Model of electroweak interactions is not the final theory valid up to very high scales. Nevertheless the model is able to describe all experimental data up to now with a typical precision around one per mille [1]. At a linear  $e^+e^-$  collider that can run at centre of mass energies,  $\sqrt{s}$ , between the Z-pole and around 1 TeV one expects to see finally deviations from the Standard Model predictions. These deviations in precision measurements occur typically for two reasons. If the new physics occurs in loop diagrams their effect is usually suppressed by a loop factor  $\alpha/4\pi$  and very high precision is required to see it. If the new physics occurs already on the Born level but at very high masses, the effects are suppressed by a propagator factor  $\frac{s}{(s-m_{NP}^2)+im_{NP}\Gamma}$  so that it is important to work at the highest possible energies. Both effects have already been used successfully in the past. PEP, PETRA and TRISTAN have been able to measure the fermion couplings to the Z although they were running at energies roughly a factor two below the resonance pole [2]. Ten years ago LEP could predict the mass of the top from its loop effects [3], exactly where it was

found at the TEVATRON later [4]. Today we are able to limit the Higgs mass to roughly 200 GeV from loop effects at LEP, SLD and the TEVATRON (figure 1) or to set limits of about 500 GeV on the mass of a hypothetical Z' boson from two fermion production at LEP II (figure 2) [5]. In the same way we expect that in ten years from now a linear collider will estimate, depending on the physics scenario nature has chosen, model parameters in a supersymmetric theory from high statistics running at the Z resonance or the mass of a techni- $\rho$  resonance from W-pair production at high energies [6].

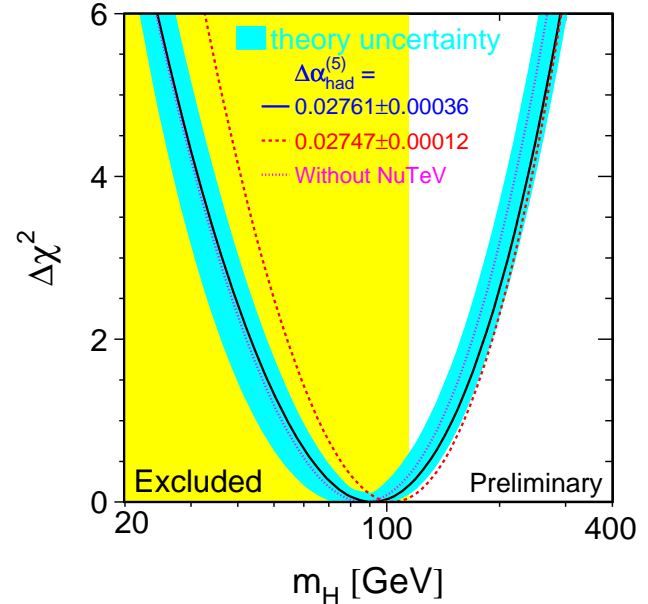


Figure 1: Prediction of the Higgs mass from the electroweak precision data.

There are several types of reactions to test the Standard Model or to investigate alternative theories. With two fermion or four fermion production on the Z-pole or close to the W-pair production threshold one can improve on the measurements done at LEP and SLD by an order of magnitude. Two fermion production at high energies is sensitive to contact interactions in general or more specific to heavy Z'-bosons or models with extra space dimensions. Four or six fermion production at high energy has a large contribution from multi gauge boson production which is sensitive to gauge boson couplings. This is especially interesting if no elementary Higgs boson exists and the electroweak symmetry is broken by a new strong interaction at a high scale.

In the following sections the results of the “Electroweak Gauge Theories and Alternative Theories” group of the

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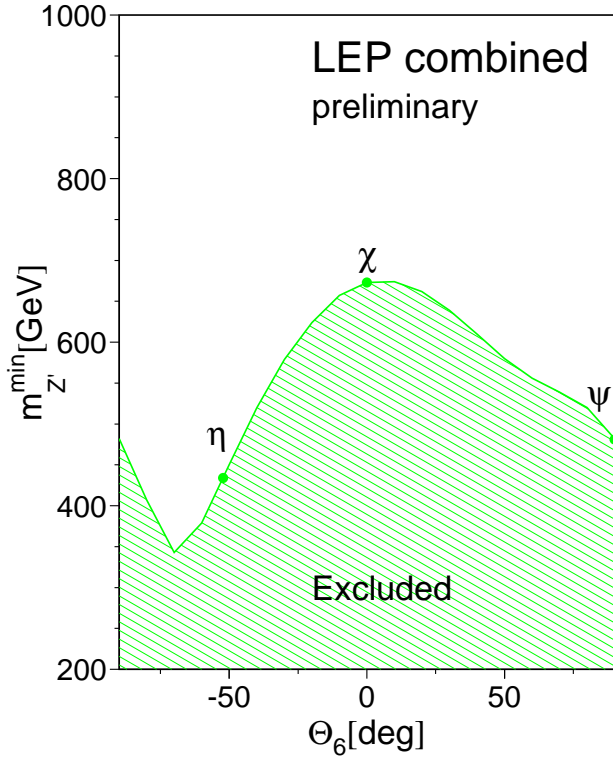


Figure 2: Exclusion of  $Z'$  within E(6) models from LEP.

ECFA/DESY linear collider workshop will be discussed with particular emphasis on the progress since the TESLA TDR [6] in March 2001.

An essential ingredient for all precision measurements are accurate Standard Model calculations which are needed to one or two loop precision. Quite some progress has been made in the last years and many more calculations are still under way. This work is summarised in a special contribution to these proceedings [7].

## THE GIGA-Z SCENARIO

The main physics goals of the Giga-Z scenario are a measurement of the effective leptonic weak mixing angle with a precision of  $\Delta \sin^2 \theta_{eff}^l = 0.000013$  from the left-right asymmetry, which would be an improvement of a factor 13 from LEP/SLD and a measurement of the W-mass with an experimental accuracy of  $\Delta m_W = 6$  MeV, improving the present LEP/TEVATRON result by a factor six [6]. While the  $\sin^2 \theta_{eff}^l$  measurement has no competition at any other machine the LHC has the goal to measure the W-mass with a precision of 15 MeV [8]. The anticipated Giga-Z accuracy is shown in figure 3 [9] compared to the present and LHC precision and to the predictions of the Standard Model and the MSSM.

The experimental requirements for this measurement are a luminosity of  $\mathcal{L} \approx 5 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$  at  $\sqrt{s} \sim m_Z$  which allows to record  $10^9$  Z-decays in less than a year, electron and positron polarisation to measure polarisation mainly from data, a beam energy measurement of  $\Delta\sqrt{s} = 1$  MeV

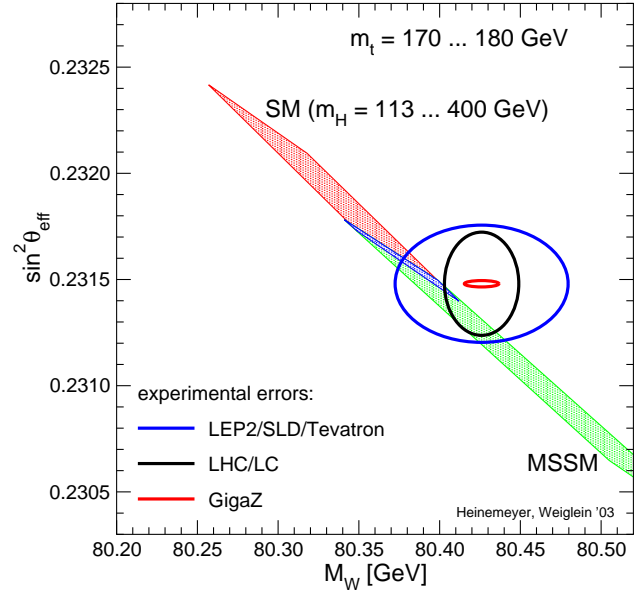


Figure 3: Expected precision for  $m_W$  and  $\sin^2 \theta_{eff}^l$  at Giga-Z compared to the present situation and to the LHC expectation. LHC/LC denotes LC high energy running only.

relative to  $m_Z$  close to the Z-peak and an extrapolation from  $m_Z$  to  $2m_W$  with  $\Delta\sqrt{s}/\sqrt{s} < 5 \cdot 10^{-5}$  and control of the beamstrahlung on the few % level. If also the Z-partial width measurements shall be improved, an absolute measurement of the luminosity with a precision of  $\Delta\mathcal{L}/\mathcal{L} = 10^{-4}$  is needed [10, 11, 12].

Excellent polarimeters are needed for relative measurements like time dependencies or the polarisation difference between positive and negative helicities of the beam particles. Detailed design studies for polarimetry, beam energy measurement, measurement of the beamstrahlung and of the luminosity are currently under way [13, 14].

Significant progress was achieved on the theoretical side. The largest parametric uncertainty for the measurement of  $\sin^2 \theta_{eff}^l$  is the uncertainty in the hadronic contribution to the running of the fine structure constant up to the Z-mass,  $\alpha(m_Z^2)$ . Not to be limited too much by the knowledge of  $\alpha(m_Z^2)$  the hadronic cross section  $\sigma(e^+e^- \rightarrow q\bar{q})$  needs to be known with 1% precision up to the  $\Upsilon$  region [15]. CMD II basically achieved this goal in the  $\rho$  region [16, 17], however there are some discrepancies with the  $\tau$  spectral functions [18, 19]. In the region  $2 \text{ GeV} < \sqrt{s} < 5 \text{ GeV}$  BES II improved the data recently from 20% to 7% accuracy [20] and further progress is possible. In addition precise results from radiative return experiments at DAΦNE, CESR and the b-factories can be expected in the near future.

Significant progress has been achieved also in the prediction of the W-mass. The calculation of  $m_W$  from the Fermi constant and  $m_Z$  is now complete to second order plus the  $m_t$  dependent 3-loop corrections [7]. This results in an uncertainty in the  $m_W$  prediction of around 3 – 4 MeV. For  $\sin^2 \theta_{eff}^l$  some 2-loop contributions are still missing and the theoretical uncertainty is estimated to

be  $\Delta \sin^2 \theta_{eff}^l = 0.00006$  much larger than the experimental goal [21]. Also some other complicated calculations that are necessary for Giga-Z are not yet done and there is still a long way to go.

### $e^+e^- \rightarrow f\bar{f}$ AT HIGH ENERGY

The most general parameterisation for new physics at high scales are contact interactions. For very large masses of the exchange particles the propagator goes like

$$\left| \frac{1}{s - M^2} \right| \approx \left| \frac{1}{t - M^2} \right| \approx \frac{1}{M^2}$$

so that the new interaction can be parameterised in a contact term  $\frac{1}{\Lambda^2}$  which is equal to  $\frac{g^2}{16\pi M^2}$  in gauge theories.

Since the experimental sensitivity to the contact term comes mostly from the interference with the Standard Model amplitude the helicity structure is important. TDR studies at  $\sqrt{s} = 800$  GeV gave typical limits around 50 TeV for  $e^+e^- \rightarrow \mu^+\mu^-$  and  $e^+e^- \rightarrow b\bar{b}$ . The LHC reaches similar limits, however mainly for the coupling between leptons and light quarks. Figure 4 shows the linear collider reach in  $\Lambda$  for  $e^+e^- \rightarrow \mu^+\mu^-$ ,  $\sqrt{s} = 500$  GeV and  $\mathcal{P}_e = 0.8$  as a function of the integrated luminosity [22]. In a recent study the sensitivity of Bhabha and Moller scattering to contact interactions has been studied [23]. It was found that the limits can be improved by typically 20% compared to muons. Due to the lower luminosity in  $e^-e^-$  running compared to  $e^+e^-$  the sensitivities in Bhabha and Moller scattering are about the same.

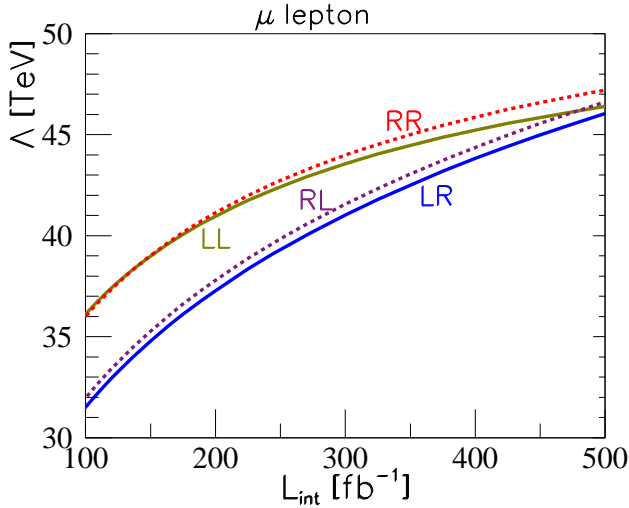


Figure 4: Contact interaction reach of the linear collider for  $e^+e^- \rightarrow \mu^+\mu^-$ ,  $\sqrt{s} = 500$  GeV and  $\mathcal{P}_e = 0.8$  as a function of the integrated luminosity.

### Models with $Z'$

There are two approaches to study models with a  $Z'$  at a linear collider. In a model dependent study one assumes

that one knows the model so that the  $Z'$ -mass is the only free parameter. In this case all couplings are fixed and any deviation of a measurement from the Standard Model value translates directly into a value of the  $Z'$ -mass. All final states can be used in this case. As for the contact terms there is a large difference between the models since the main sensitivity comes from the interference term. Figure 5 compares the reachable  $Z'$  masses for different models at the linear collider and the LHC [24]. On average the reachable masses are similar for both machines and around 4 TeV.

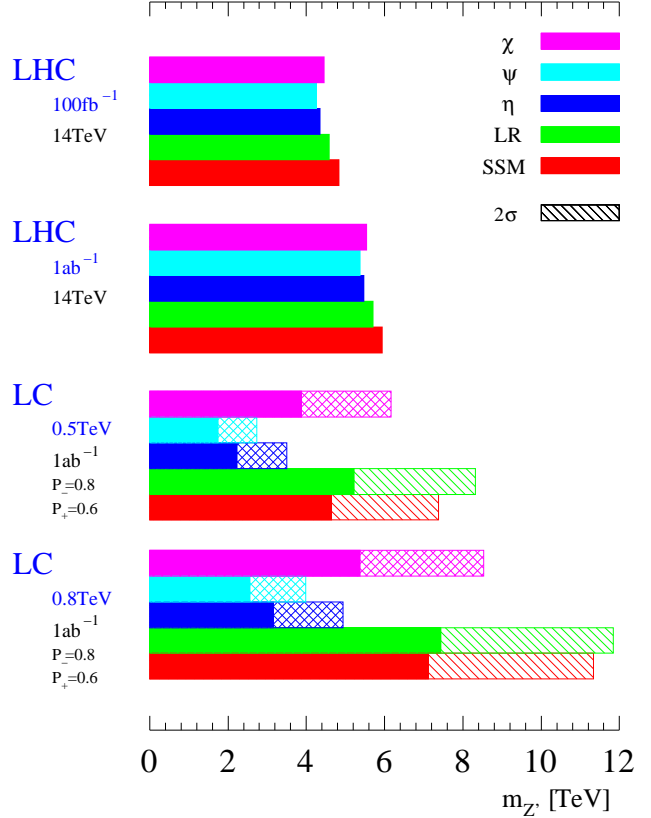


Figure 5: Mass reach for a  $Z'$  in different models for LHC and LC. The solid bars correspond to a  $5\sigma$  discovery, while the dashed ones correspond to a  $2\sigma$  exclusion.

In a model independent approach the  $Z'$  mass and the  $Z'$  couplings are considered simultaneously as free parameters. Any observable is given as the product of initial state and final state couplings, so that a  $Z'$  remains invisible in  $e^+e^-$  if it does not couple to leptons. For this reason hadronic events can be used only when non-zero  $Z'$ -lepton couplings are already established. At a given centre of mass energy a linear collider is sensitive to the normalised couplings

$$a_f^N = a'_f \sqrt{\frac{s}{m_{Z'}^2 - s}}$$

$$v_f^N = v'_f \sqrt{\frac{s}{m_{Z'}^2 - s}}$$

which can be measured for leptons in a model independent way using cross sections and asymmetries. A  $Z'$  model is then defined as a line in the  $a_f^N - v_f^N$  plane where the exact position is given by the  $Z'$  mass. Figure 6 shows the sensitivity of the linear collider assuming for the central value a  $\chi$ -model with  $m_{Z'} = 6$  TeV, which is outside the LHC sensitivity [24]. Also shown is the prediction for several E(6) models, where  $\chi$ ,  $\psi$ ,  $\eta$  stands for different mixing angles between the gauge bosons from the  $U(1)_\chi$  and  $U(1)_\psi$  gauge group [25]. The different models can be clearly separated with high luminosity.

In the ideal case the LHC finds a  $Z'$  and measures its mass so the linear collider can measure the couplings. Figure 7 shows the LC sensitivity in this case for different models and different assumptions on  $\sqrt{s}$  and  $m_{Z'}$  [6]. In general the couplings can be measured with a precision of a few percent.

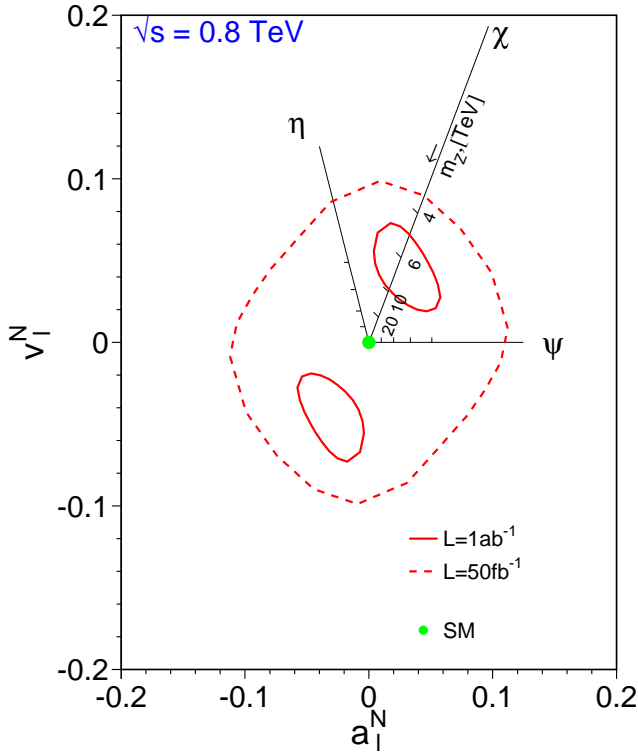


Figure 6: Measurement of normalised  $Z'$  couplings at TESLA. The  $\chi$ -model with  $m_{Z'} = 6$  TeV is assumed for the central value.

For the left-right symmetric model an analysis on the one loop level has been performed [26]. In this model the quadratic top mass dependence of  $\Delta\rho$  is suppressed by a term  $\frac{M_{W_1}^2}{M_{W_2}^2 - M_{W_1}^2}$  where  $W_1$  is the observed W-boson and  $M_{W_2} > 500$  GeV. The successful prediction of  $m_t$  at LEP was therefore a pure accident and the heavy Higgs and right handed neutrino masses need to be fine tuned to fit the LEP/SLD precision data.

Another study analysed the sensitivity to  $Z$ - $Z'$  mixing one can get from the Z-data and the W mass [27]. As an

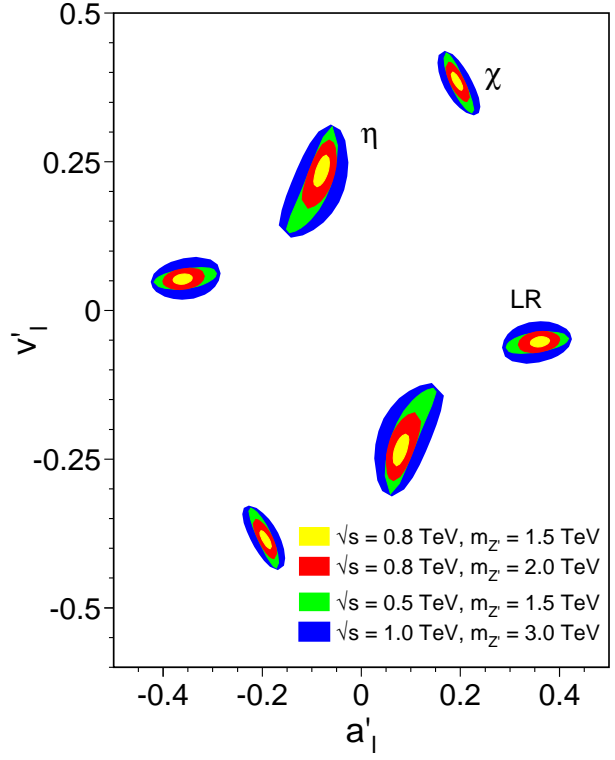


Figure 7: Measurement of the  $Z'$  couplings at a linear collider for different  $Z'$  masses and centre of mass energies.

example figure 8 shows the current measurements and the Giga-Z expectation compared to several  $Z'$  models assuming that a 115 GeV Higgs has been found. It can be seen that apart from  $\sin^2 \theta_{eff}^l$  and  $m_W$  an accurate measurement of the leptonic decay width of the Z,  $\Gamma_l$ , is useful as well.

### Extra space dimensions

The linear collider and the LHC are sensitive to the presence of extra space dimensions via effects from Kaluza Klein tower graviton ( $G^*$ ) exchange. In the TDR it has been shown that there are visible effects from  $e^+e^- \rightarrow \gamma G^*$  and  $e^+e^- \rightarrow G^* \rightarrow f\bar{f}$  for an extra dimension scale of  $M_H < 8$  TeV and  $\sqrt{s} = 800$  GeV. The reach of LHC is similar. Recently the emphasis has been put on the question how one can distinguish an extra dimensions signal from a  $Z'$  in case a deviation from the Standard Model is seen. Here one can use the fact that the Graviton is a tensor particle.

If one defines the moments  $\langle P_n \rangle = \int dz \frac{1}{\sigma} \frac{d\sigma}{dz} P_n(z)$ , where the  $P_n$  are the Legendre polynomials and  $z = \cos \theta$  is the cosine of the polar angle, one can show that for vector or scalar particle s-channel exchange  $\langle P_n \rangle = 0$  for  $n > 2$  while for tensor particle exchange  $\langle P_{3,4} \rangle \neq 0$  [28]. A unique identification of tensor particle exchange can be achieved up to around 5 TeV with  $\sqrt{s} = 800$  GeV,  $\mathcal{L} = 1 \text{ ab}^{-1}$  and electron (positron) polarisation of 80% (60%). Similar results can be obtained with specially constructed asymmetries [29].

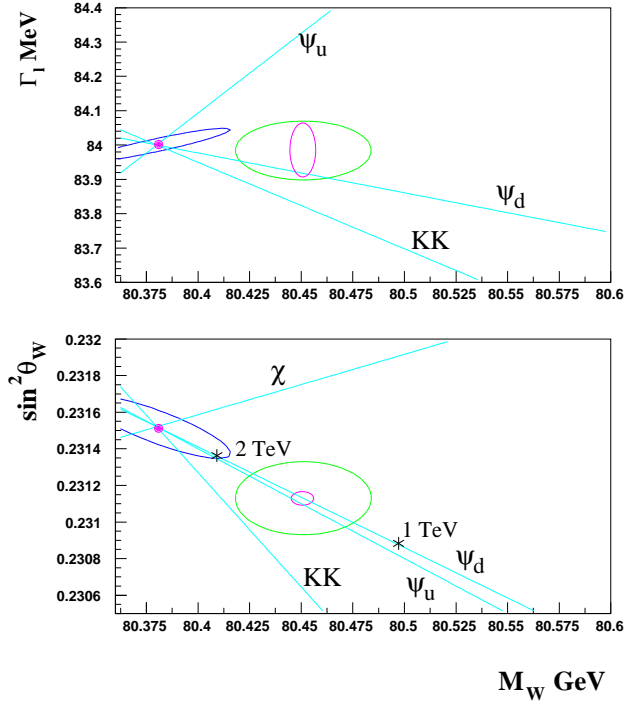


Figure 8: Predictions of several models with a  $Z'$  compared to the present and predicted Giga-Z precision data. The ellipse around the crossing point indicates the uncertainty from the present day error on  $m_t$  and  $\alpha(m_Z)$ .

If transverse beam polarisation is available for both beams one can measure the azimuthal asymmetry as a function of the polar angle [30]. Figure 9 shows this asymmetry for leptons b- and c-quarks for the Standard Model and for  $M_H = 1.5$  TeV. Using this asymmetry extra dimensions can be excluded up to  $M_H < 10(22)$  TeV for  $\sqrt{s} = 0.5(1)$  TeV, which is the highest reach at a next generation collider. For vector and scalar particle exchange the azimuthal asymmetry is symmetric in  $\cos \theta$ , while it is asymmetric if also tensor particle exchange is present. This allows to distinguish extra dimensions from  $Z'$  exchange up to  $M_H < 10\sqrt{s}$ .

### CP violation in $\tau$ production

In the Standard Model the CP-violating dipole moment of the  $\tau$  lepton is extremely small ( $\sim 10^{-34}$  e cm). However for example in models with Majorana neutrinos or in CP violating two Higgs doublet models these moments can be of order  $10^{-19}$  e cm.

It has been studied how well the electric and weak dipole moment can be measured in  $\tau$  pair production at TESLA using spin correlations and polarised beams [31]. For this analysis  $\tau \rightarrow \pi\nu$  and  $\tau \rightarrow \rho\nu$  decays have been used and CP-odd vector correlations between the two  $\tau$ s have been constructed. At  $\sqrt{s} = 800$  GeV the real parts of the weak and the electromagnetic dipole moment can be measured with a precision of  $3 - 4 \cdot 10^{-19}$  e cm which touches the interesting region. For the imaginary parts the precision is

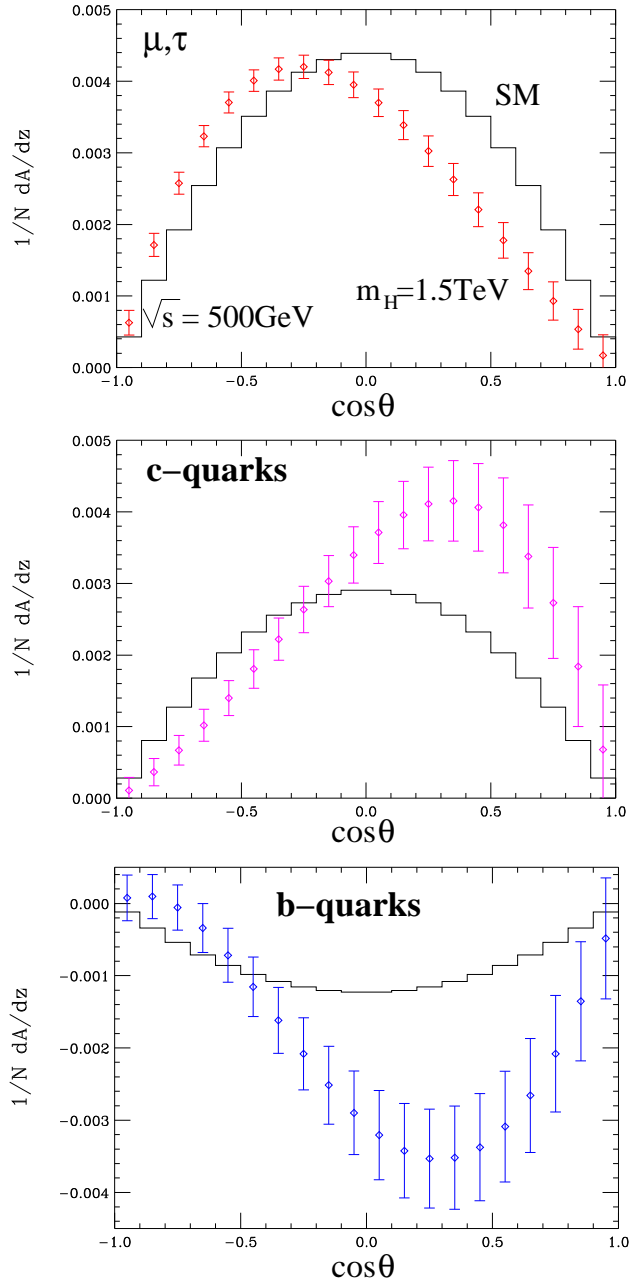


Figure 9: Azimuthal asymmetry with transverse beam polarisation as a function of the polar angle for leptons b- and c-quarks for the Standard Model and for  $M_H = 1.5$  TeV.

about three orders of magnitude worse.

### GAUGE BOSON PRODUCTION

High precision measurements of gauge boson production are interesting in several aspects. The interactions amongst gauge bosons are directly given by the structure of the gauge group. The longitudinal gauge bosons are connected to the mechanism of electroweak symmetry breaking so that their interactions can teach us about this mechanism in case no elementary Higgs boson exists. In a strongly in-



interacting theory the longitudinal components of the gauge bosons are expected to have similar interactions at very high energies as the pions in QCD at low energy.

In a weakly interacting theory including an elementary Higgs boson gauge boson self-interactions should receive loop corrections of  $\mathcal{O}(\frac{g^2}{16\pi^2}) \sim 3 \cdot 10^{-3}$ . If the experimental precision is larger than this number gauge boson interactions should be able to test the then Standard Model in the same way as  $\sin^2 \theta_{eff}^l$  and  $m_W$  do it now.

For the TDR a detailed study including full detector simulation has been done for  $e^+e^- \rightarrow W^+W^-$  [32]. It has been found that the C, P conserving couplings can be measured with a precision of  $3-15 \cdot 10^{-4}$  at  $\sqrt{s} = 500$  GeV and around a factor two better at  $\sqrt{s} = 800$  GeV. This is much better than the expected effects from radiative corrections so that W-pair production will become a new precision observable. In a strongly interacting scenario this precision translates into a new physics scale of  $\Lambda > 10$  TeV which is also significantly above the  $\Lambda \leq 3$  TeV limit from unitarity. The C or P violating couplings can be measured roughly one order of magnitude worse than the C, P conserving ones.

Recently a study using optimal observables has been done [33]. This work is on parton level only up to now, but it has shown that the imaginary parts of the couplings can be measured simultaneously with the real parts with about the same precision and without degrading the precision of the real parts. Only one combination of couplings ( $\text{Im}(g_1^R + \kappa_R)$ ) cannot be measured with longitudinal beam polarisation. If transverse beam polarisation is available this coupling can be measured. In this case, however, the precision of the other coupling is degraded by roughly a factor of two [34].

Also the measurement of the triple gauge couplings at a photon collider in  $\gamma\gamma \rightarrow WW$  and  $e\gamma \rightarrow W\nu$  has been studied, using hadronic W decays only. The study of  $e\gamma \rightarrow W\nu$  is reasonably complete [35], while in  $\gamma\gamma \rightarrow WW$  the azimuthal decay angle,  $\phi$ , which is sensitive to the interference of the different helicity amplitudes is still missing [36]. Both reactions can be selected cleanly with an overall efficiency around 80%. Figure 10 shows the polar angle distribution for  $e\gamma \rightarrow W\nu$  and the background after cuts on the visible energy and the invariant mass. In the real  $e\gamma$  mode, where only one beam is converted, only some background in the extreme forward and backward regions is left from  $e\gamma \rightarrow Ze$  and from  $\gamma\gamma$  induced hadron production which can easily be rejected by an angular cut. In the parasitic mode, where the  $e\gamma$  luminosity during  $\gamma\gamma$  running is used, some additional background from  $\gamma\gamma \rightarrow WW$  where one W decays leptonically is left.

The cross sections in these two channels are much larger than in  $e^+e^-$ . However there are no large gauge cancellations so that the final precision is comparable in all cases. Figure 11 compares the expected precision for  $\kappa_\gamma$  and  $\lambda_\gamma$  at the different machines. For  $\gamma\gamma$  and  $e\gamma$  a 0.1% error on the luminosity is assumed. It should be noted that  $\kappa_\gamma$  is very sensitive to the luminosity error and to uncertainties

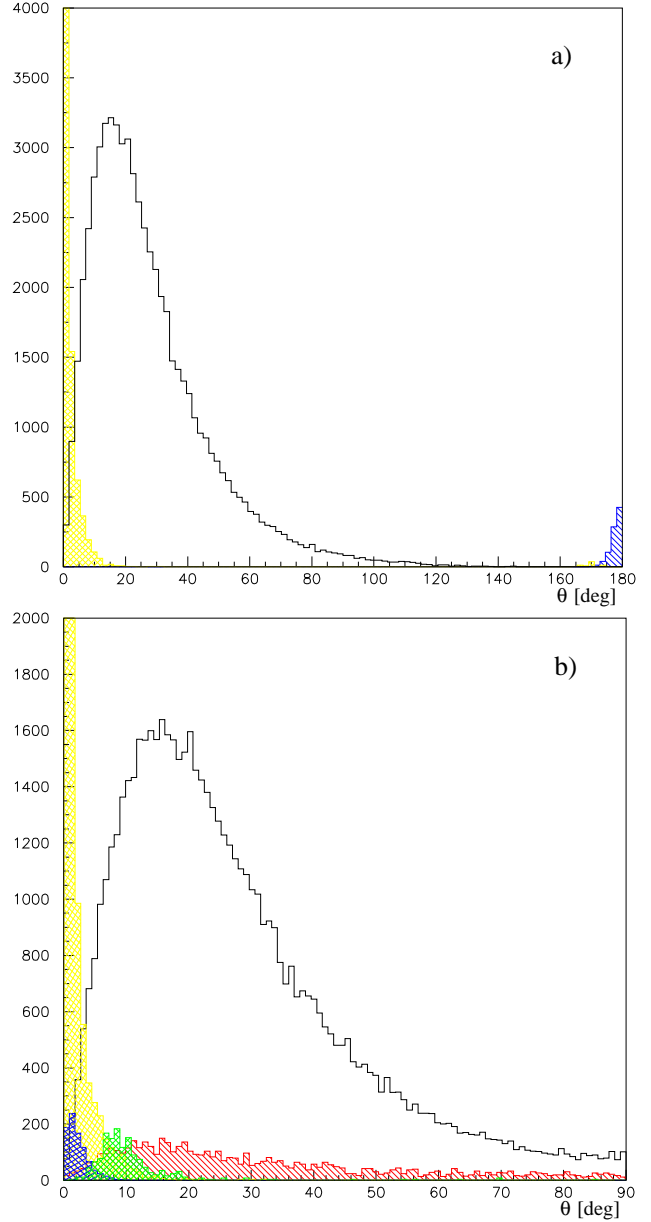


Figure 10: Signal and background for  $e\gamma \rightarrow W\nu$  in the real  $e\gamma$  mode (a) and from the parasitic  $\gamma\gamma$  running (b). The white area represents the signal. In a) the hatched contribution on the left is from  $\gamma\gamma$  induced processes and the one on the right from  $e\gamma \rightarrow eZ$ . The additional cross-hatched (green) contribution in b) is from  $\gamma\gamma \rightarrow q\bar{q}$  and the singly hatched (red) from  $\gamma\gamma \rightarrow WW$ .

in the polarisation while  $\lambda_\gamma$  is basically insensitive to these effects. For  $e\gamma$  the improvement using the  $\phi$  angle in the fit is a factor seven for  $\lambda_\gamma$ , a similar factor can be expected for  $\gamma\gamma$  as well. In summary  $\kappa_\gamma$  will be measured significantly worse in  $e\gamma$  and  $\gamma\gamma$  than in  $e^+e^-$ , however still good enough for cross checks in case deviations from the Standard Model are found. For  $\lambda_\gamma$  the photon collider could give the best result.

In an alternative study the leptonic W decays in  $e\gamma \rightarrow$

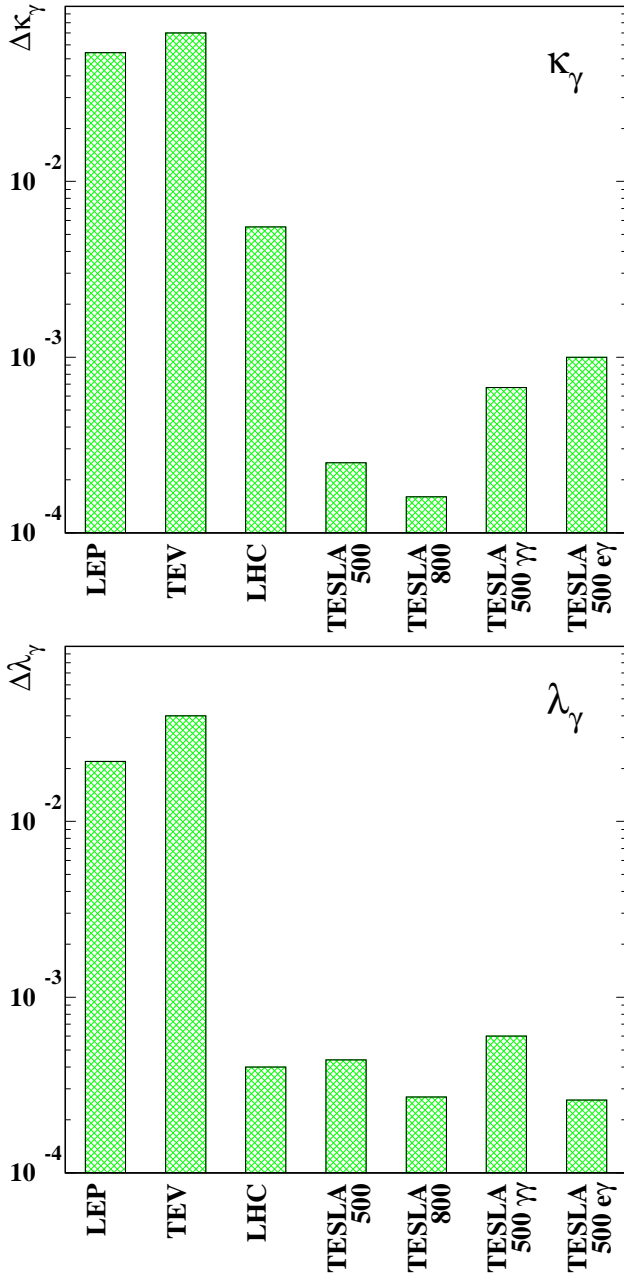


Figure 11: The expected precision for  $\kappa_\gamma$  and  $\lambda_\gamma$  at different machines.

$W\nu$  have been considered [37]. In these events only a single lepton is seen in the detector. The couplings have been measured from the cross section in an optimised phase space region where background and the variable photon energy has been taken into account. Assuming no error on the normalisation, the error in  $\kappa_\gamma$  is similar for the two analyses taking the lower leptonic branching ratio of the  $W$  into account. For  $\lambda_\gamma$  the error in the leptonic analysis is significantly larger because of the missing information due to the second missing neutrino.

It is known since long that  $e^+e^- \rightarrow W^+W^-$  is sensitive to technicolour vector resonances in the same way as the

$\rho$  is seen in  $e^+e^- \rightarrow \pi^+\pi^-$  [38]. It has been shown now, that  $\gamma\gamma \rightarrow W^+W^-$  is sensitive to rescattering effects from a scalar or a tensor resonance [39]. Figure 12 compares the cross section for longitudinal gauge boson production in the central region for the Standard Model and for a tensor resonance with a mass of 2.5 TeV. An experimental study, if these effects are measurable at TESLA, is planned.

These studies underline the importance to measure the gauge couplings in several different channels. For example a vector resonance would result in anomalous gauge couplings in  $e^+e^-$  while in  $\gamma\gamma$  and  $e\gamma$  one might still measure the Standard Model values.

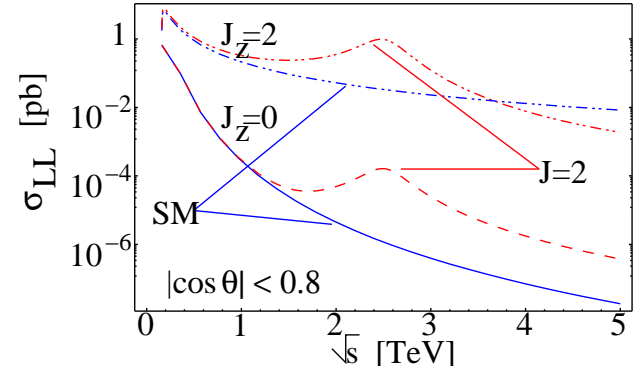


Figure 12: Cross section for longitudinal  $W$ -pair production in  $\gamma\gamma$  scattering for the Standard Model and in presence of a tensor resonance with 2.5 TeV mass.  $J_z$  denotes the spin of the  $\gamma\gamma$  system.

The reaction  $\gamma\gamma \rightarrow W^+W^-$  is also the ideal place to test for anomalous  $\gamma\gamma W^+W^-$  quartic couplings. These couplings have been first studied in  $e^+e^- \rightarrow W^+W^-\gamma$  and limits of the coupling parameters of  $\mathcal{O}(1)$  at  $\sqrt{s} = 500$  GeV have been found [40, 41]. The cross section dependence of  $\gamma\gamma \rightarrow W^+W^-$  on these couplings has been studied and limits on these couplings have been derived [42]. Figure 13 shows the cross section dependence on these couplings for  $\sqrt{s} = 1$  TeV. Without systematic uncertainties limits between  $10^{-4}$  and  $10^{-2}$  can be achieved. This is about three orders of magnitude better than the  $e^+e^-$  result.

## CONCLUSIONS

It has been shown that electroweak precision tests contribute significantly to the physics of a linear collider. Precision measurements on the  $Z$  pole can test model parameters inside or beyond the Standard Model. Two-fermion production at high energy tests a wide class of models like those containing additional  $Z'$  bosons or extra space dimensions. The limits are often comparable or better than those at the LHC.  $W$ -pair production provides new precision observables on the same level as  $\sin^2 \theta_{eff}^l$  or  $m_W$ . If no light Higgs exists, gauge boson production offers a window to strong electroweak symmetry breaking.



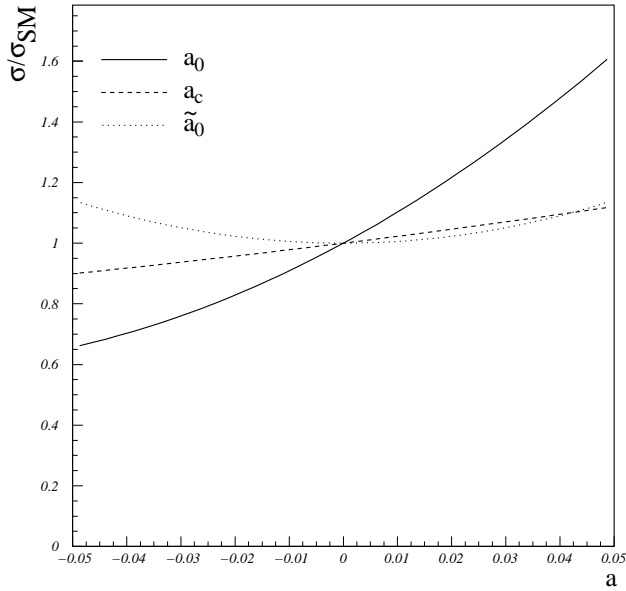


Figure 13: Dependence of  $\sigma(\gamma\gamma \rightarrow W^+W^-)$  for  $\sqrt{s} = 1$  TeV on the  $\gamma\gamma W^+W^-$  couplings. The exact definition of the couplings can be found in [41, 42].

In summary it is the combination of the direct studies of the probable extensions of the Standard Model, like Higgs and SUSY, with the potential of the precision tests that makes the Linear Collider a unique tool to understand the physics of electroweak symmetry breaking.

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